J. of Supercritical Fluids 95 (2014) 195–203

Contents lists available at ScienceDirect

The Journal of Supercritical Fluids

journal homepage: www.elsevier.com/locate/supflu

The transition to turbulence of buoyant near-critical water jets

U. Hegde [a,*], D. Gotti [a], M. Hicks [b]

[a] National Center for Space Exploration Research, Cleveland, OH, United States
[b] NASA John H. Glenn Research Center, Cleveland, OH, United States

ARTICLE INFO

Article history:
Received 11 April 2014
Received in revised form 8 August 2014
Accepted 8 August 2014
Available online 19 August 2014

Keywords:
Transition
Turbulence
Jets
Supercritical

ABSTRACT

Observations of near-critical water jets are reported in the injection Reynolds number range of approximately 300–3000 to characterize their transition to turbulence. Three types of cases are described: (i) subcritical jet injected into subcritical water, (ii) supercritical jet injected into supercritical water, and (iii) supercritical jet injected into subcritical water. In each case, the working pressure was kept above the critical value to eliminate two-phase effects. For cases (i) and (ii), the transition behavior follows well known characteristics with transition to turbulence initially occurring near the tip of the jet with the transition location moving upstream nearer to the nozzle exit with an increase in injection Reynolds number. However, the transition behavior for case (iii) is quite different with significant buoyant effects leading to turbulent behavior at lower Reynolds numbers. Consideration of the pseudocritical region with strongly varying fluid properties, which is established in the mixing region between the jet and the cell fluid, yields an effective Froude number that is useful to elucidate this difference. The effective Froude number incorporates the Prandtl number of the mixing region to account for the large disparity between viscous and thermal length scales.

© 2014 Elsevier B.V. All rights reserved.

1. Introduction

Supercritical Water Oxidation (SCWO) systems take advantage of the behavior of water at supercritical temperatures and pressures. At these conditions, changes in transport properties, thermal and state variables (e.g., density, specific heat, specific enthalpies), and solvating properties allow for extremely high reaction rates and conversion efficiencies over a wide range of waste streams [1,2]. Depending on the design of the SCWO system and the waste feed stream, conversion efficiencies as high as 99.99% with reaction times on the order of milliseconds can be achieved [3,4].

Many SCWO reactor configurations have been studied to date. These include continuously stirred reactors, transpiring wall reactors, flow-through reactors, and centrifugal reactors. In many instances, control of the solid phase (e.g., precipitated salts) drives the reactor design since this contributes to reactor foul up, plugging, and corrosion. However, it has been suggested that, from a chemical process point of view, SCWO reactors may be broadly classified as either flow-through or batch feed systems [5].

In the batch system, both the oxidizer and the waste to be oxidized are mixed with the water and the system is brought up to supercritical conditions. Thus, mixing at the molecular level is assumed to occur prior to onset of the chemical reaction. Such systems may be identified as premixed with the chemical conversion rate controlled by the chemical kinetics.

Flow-through systems are characterized by the inflow of reactants into the supercritical water reactor and the outflow of the reacted contents. The inflow stream, or jet, is generally a mixture of the oxidizer and fuel (i.e., the waste to be oxidized). Depending on the extent of energy release, the reaction may then become self-sustaining and the length of the reactor and the subsequent residence time of the reactants in the supercritical region of the reactor vessel become critical design parameters. The input reactants are also often introduced separately where either the fuel or oxidizer is introduced after the bulk fluid has reached supercritical conditions. Chemical conversion occurs only after molecular contact between the oxidizer and the waste takes place. This is enhanced by "bulk fluid mixing" which increases the contact between regions of separate reactants; however, contact at the molecular level depends upon species diffusion rates.

Gravity directly effects the distribution of the reactant and product species by influencing the velocity field. Buoyant convection arises due to density gradients and in SCWO these may arise from temperature and/or composition gradients when the pressure is

* Corresponding author at: MS 110-3, NASA John H. Glenn Research Center, Cleveland, OH 44135, USA. Tel.: +1 216 433 8744; fax: +1 216 433 3793.
E-mail addresses: uday.g.hegde@nasa.gov (U. Hegde), daniel.j.gotti@nasa.gov (D. Gotti), michael.c.hicks@nasa.gov (M. Hicks).

http://dx.doi.org/10.1016/j.supflu.2014.08.005
0896-8446/© 2014 Elsevier B.V. All rights reserved.

kept fixed. The effect of composition is reflected in the local density, ρ, as follows:

$$\rho = \sum_i \rho_i = \sum_i \rho Y_i \tag{1}$$

where ρ_i is the density of the pure component i and Y_i is the local mass fraction of species i, assuming volume changes due to mixing are negligible. The dependence of the density on temperature, T, is given by the isobaric thermal expansion coefficient, β,

$$\beta = -\left(\frac{1}{\rho}\right)\left(\frac{\partial \rho}{\partial T}\right)_P \tag{2}$$

While detailed properties of waste streams in the supercritical region are not generally available, some guidance on the influence of the variation of density with temperature may be obtained from the equation of state of the working fluid. For example, generalized equations of state have been proposed for high pressure and temperature which are generally assumed to be suitable for supercritical conditions [6].

In general, the importance of gravity is quantified by considering the momentum equation. Two bounding cases arise depending upon the Reynolds number, Re, of the injected flow. If $Re \gg 1$, the parameter to consider is the Froude number, F, defined here as the ratio of the inertia force of the injected jet to the buoyancy force acting on the jet in the vicinity of the nozzle, with

$$F^2 = \frac{U_j^2}{g d_v} \frac{\rho_j}{(\rho_c - \rho_j)} \tag{3}$$

where the subscript j refers to jet quantities, the subscript c refers to the cell's bulk fluid, U_j is the jet velocity, d_v is the shear layer momentum thickness generally of the order of the injection nozzle diameter d, and g is the acceleration due to gravity.

On the other hand, if $Re \sim O(1)$, the viscous forces become important and the Rayleigh number, Ra, which is the ratio of the buoyancy force to viscous force must be considered. Ra is defined as:

$$Ra = \left(\frac{\rho_c - \rho_j}{\rho_j}\right) \frac{g d_v^3}{\alpha \nu} \tag{4}$$

where α and ν are the thermal diffusivity and kinematic viscosity of the jet fluid.

Supercritical flow-through systems have frequently been studied in tubular configurations to assess heat transfer and flow characteristics [7]. Most of these studies have been in the turbulent regime and buoyancy effects have been found to be important in the heat transfer characteristics.

Supercritical water jets have been studied less frequently. For example for submerged jets, a series of detailed experiments with co-flowing hydrothermal flames and supercritical water jets has been conducted with application to hydrothermal spallation drilling [8]. This study considered co-flowing supercritical fuel and oxidizer flows in a shroud of subcritical cool water. Temperature measurements as well as flame and flow images were obtained. The studies were in the turbulent regime with Reynolds numbers greater than 10,000 and Froude numbers in excess of 25. In another study, neutron radiography was employed to investigate reversing supercritical water jets [9]. A conclusion of this latter study was that buoyant forces strongly influenced the flow patterns. However, the flow details were smeared out because of the large (~3 s) temporal resolution of the radiography diagnostic. Significant buoyant effects were also noted during studies of salt precipitation in supercritical water jets [10]. Limited SCWO studies have been conducted in a drop tower environment to suppress the effects of buoyancy [11,12] for laminar and turbulent flow conditions. These showed changes in the temperature field as compared to the buoyant case but no flow visualization was attempted.

There is a lack of observational studies of the transition to turbulence of near-critical water jets in non-tubular, and relatively large chambers (i.e., where the characteristic dimension of the cell divided by the nozzle diameter is $\gg 1$) to simulate free jet behavior. This shortcoming is, in part, due to difficulties associated with the installation and maintenance of optical quality windows of sufficient size to image the flow field. In particular, leaks of fluid around the window seals, and degradation of the optical quality over time are key issues. However, free jets have the advantage, unlike tubular flows, that wall interaction effects are small and attention can be focused on the dynamics of the shear layer formed between the jet and the surrounding fluid. The effect of buoyancy on the jet behavior can also be studied. These advantages are the primary motivation for the studies of free near-critical water jets described in this paper. It is expected that the obtained data may also help in improving theoretical models of near-critical flows which may then be applied to other configurations. The results may also be useful in assessing regimes of operation of supercritical water reactors and/or supercritical water flow loops.

The transition to turbulence of liquid water jets into liquid water that is near atmospheric conditions has been well studied [13,14]. Both buoyant and non-buoyant jets have been investigated. Buoyancy effects may be introduced by either injecting the jet fluid at a different temperature, or by varying its composition, with respect to the surrounding fluid. In both cases, the effect is to change the relative densities of the jet fluid and the surrounding fluid and change the value of the Froude number, F (Eq. (3)). A major characteristic of both the non-buoyant and buoyant jets is the existence of a "breakpoint distance" along the length of the jet, downstream of which the jet becomes turbulent. The breakpoint shifts upstream with increase in the injection Reynolds number and finally the entire jet becomes turbulent if the Reynolds number is high enough. For example, non-buoyant liquid water jets become fully turbulent between a Reynolds number of 2000 and 3000. The Reynolds number for transition to turbulence of heated buoyant water jets generally decreases as the Froude number, F, is decreased. However, because of the relatively weak dependence of density with temperature near atmospheric conditions, the Froude numbers achieved have been relatively large, i.e., of O(10) and higher.

In this paper, experimental observations on the transition to turbulence of different near-critical water jet configurations are discussed. The water jet is injected vertically upward into a test cell kept at approximately isobaric conditions by means of a back pressure regulator. Specifically, three different configurations at near-critical conditions are considered: (i) subcritical jet injected into subcritical water, (ii) supercritical jet injected into supercritical water and (iii) supercritical jet injected into subcritical water. In all cases, the operating pressure is above the critical value so that phase change effects are not involved. The temperature of the injected water was kept higher than that of the cell fluid in the experiments discussed here so that the buoyant force would tend to accelerate the jet. Injection Reynolds number varied from approximately 300 to 3000, and the Froude number was from less than 1 to 10. It has been suggested that buoyant effects are truly negligible only for Froude numbers in excess of 50 [13] so all of the jets in the present study are expected to be influenced by buoyancy to some degree.

Some tests were also conducted with subcritical water jets injected into supercritical water. For these cases, the temperature of the injected water is lower than that of the water in the cell. At low and moderate injection Reynolds number up to approximately 1000, the buoyancy decelerated the denser upward directed jet flow to such an extent that the injected fluid just spilled over the nozzle and began pooling at the bottom of the test cell. The pooled liquid level increased with time as injection proceeded. This region appeared dark in the images, possibly due to refractive

Download English Version:

https://daneshyari.com/en/article/6671147

Download Persian Version:

https://daneshyari.com/article/6671147

Daneshyari.com